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We demonstrate the generation of 99 fs pulses by a mode-locked laser oscillator built around a Yb:CaF_2 crystal. An average power of 380 mW for a 13 nm bandwidth spectrum centered at 1053 nm is obtained. The short-pulse operation is achieved thanks to a saturable absorber mirror and is stabilized by the Kerr lens effect. We investigated the limits of the stabilization process and observed a regime slowly oscillating between mode locking and Q switching. © 2009 Optical Society of America

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In the past decade, laser development using Yb-doped materials and especially crystals has become one of the most active fields in laser research. It is now widely recognized that Yb-doped crystals have a significant potential in the development of directly diode-pumped high-power and ultrashort lasers. This is possible thanks to their broad emission bands, supporting short-pulse generation, combined with their good thermal properties owing to a simple electronic-level structure based on only two manifolds.

In this context, intense interest has been raised for crystals with simple crystallographic structure, such as cubic crystals. Among them, the most studied materials are garnets such as YAG and GGG, sesquioxides such as Sc_2O_3, Y_2O_3 and Lu_2O_3, and fluorides such as CaF_2 and SrF_2. These cubic crystalline structures have two main advantages: First, they have very good thermal properties [1], with thermal conductivities on the order of 10 W/m/K for undoped crystals; second, they have the possibility to grow them, either in the form of large-size transparent ceramics [2] and single crystals, with crystals already exceeding 30 cm diameter in the case of CaF_2, or in the form of thick films by using standard techniques [3]. However, Yb-doped cubic oxides have the drawback of exhibiting relatively narrow spectral lines, preventing the generation and amplification of very short pulses [4,5]. It is possible to overcome this limitation by using a strong self-phase modulation effect in the oscillator, and Tokurakawa *et al.* have demonstrated very short pulses with Sc_2O_3, Lu_2O_3 or combining Sc_2O_3 and Y_2O_3 [6,7]. Nevertheless, cubic crystals with broader spectral bandwidths should be more convenient to generate and amplify easily short pulses.

From this point of view, fluorides and in particular Yb^{3+}-doped calcium fluoride CaF_2 (aka fluorite or fluorospar) are good candidates for the development of femtosecond lasers [8–11]. For a cubic crystal, Yb-doped fluorite has a very broad and smooth emission band. This is explained by the formation of a particular type of emitting center made of several neighboring Yb^{3+} ions [10] that only appears at a doping level above 0.5 at. % Yb. In 2004, a high-power diode-pumped Yb^{3+}:CaF_2 femtosecond laser with pulse duration of 153 fs was reported [8]. These results were very promising, but one could have expected shorter pulses considering the broadness of the emission spectrum of Yb:CaF_2. The problem in mode-locked oscillators using Yb-doped fluorite is that the limitations to reach shorter pulses are not only the limited spectral gain bandwidth but also the strong tendency of Yb:CaF_2 to Q switch [12]. This behavior is due to the very long lifetime (2.4 ms) of the metastable $^2F_{5/2}$ level, and it leads to the difficulty to stabilize a cw mode-locked (cwML) operation. In this Letter we investigate a laser cavity specifically designed to produce short pulses by enhancing the Kerr lens effect and to stabilize the cwML operation achieved through a saturable absorber. We evaluate the effects of the Kerr and of the thermal lenses to understand the specific operation regime and to optimize the design of the cavity. Limitations of the resulting short-pulse mode-locking operation using a saturable absorber mirror assisted by a Kerr lens effect are also studied.

The cavity is presented in Fig. 1. We use a 6.1-mm-long, 3 mm × 7 mm section Brewster-cut Yb:CaF_2 crystal doped with 2.6 at. % Yb. The laser waist radius in the crystal is reduced (compared with [8]) down to 33 μm × 46 μm. To optimize the overlap between the laser and pump beams, a 7 W laser diode at 979 nm (3 nm FWHM) coupled to a 50 μm diameter fiber (NA=0.22) is used. This diode is colli-

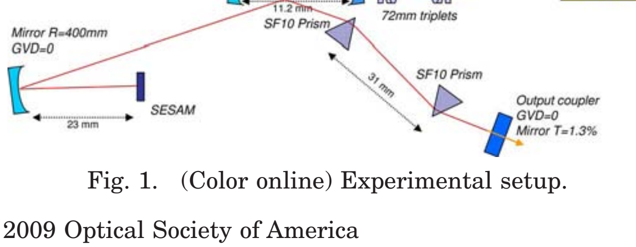

Fig. 1. (Color online) Experimental setup.

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mated and focused using two 72 mm focal-length triplets to reduce optical aberrations. To initiate the ML regime, a semiconductor saturable absorber mirror (SESAM) manufactured by Batop GmbH (SAM-294-II.23, 1045 nm, 1%) is inserted with the following characteristics: 1% saturable absorption, 1045 nm for the center wavelength, 70 μJ/cm^2 fluence saturation, and incident laser beam waist radius of 20 μm $\times$ 20 μm. The mirrors of the cavity are specified to introduce a low group-velocity delay. Although the output coupler is in the dispersive arm, the spatial chirp at the output is small compared with beam size and is not observed. The dispersion of the cavity is adjusted by a pair of SF10 prisms nominally separated by 310 mm, while the amount of dispersion added by the Yb:CaF_2 crystal is 220 fs^2.

In this configuration, the laser emits around 400 mW average power. To optimize the cwML stability using SESAM and Kerr-lens mode locking (KLM), we evaluated the thermal [13,14] and Kerr lenses in our conditions using the following equations giving the lens dioptric powers D_{th}, D_{Kerr}:

$$D_{\mathrm{th}} = \frac{1}{f_{\mathrm{th}}} = \frac{\eta_h P_{\mathrm{abs}} \chi}{2\pi {w_p}^2 \kappa_c}, \tag{1}$$

$$D_{\mathrm{Kerr}} = \frac{1}{f_{\mathrm{Kerr}}} = \frac{8 n_2 L P_{\mathrm{intra}}}{\pi {w_l}^4 f_R \Delta t}, \tag{2}$$

with thermal conductivity of the doped crystal $\kappa_c = 6.1\ \mathrm{W\,m^{-1}\,K^{-1}}$ [11], thermo-optic coefficient $\chi = -11.3\ 10^{-6}\ \mathrm{K^{-1}}$, ratio $\eta_h \approx 5\%$ of the absorbed pump power $P_{\mathrm{abs}} = 4.5$ W transferred into heat (mainly owing to fluorescence-photon quantum defect [11]), pump waist w_p, nonlinear refractive index $n_2 \approx 2.10^{-20}\ \mathrm{m^2/W}$ (independently measured by using a Z-scan technique), crystal length $L = 6.1$ mm, intracavity power $P_{\mathrm{intra}} = 40$ W, repetition rate $f_R = 113$ MHz, pulse duration $\Delta t = 100$ fs, and laser beam waist inside the crystal $w_l = 40\ \mu$m. To include the effects of divergence and astigmatism of the pump in the crystal, a convenient approximation is to integrate the thermal dioptric powers calculated on small slices of the crystal. If we consider a constant absorption (constant $\mathrm{d}P_{\mathrm{abs}}/\mathrm{d}z$), this approximation consists in taking the equivalent waist $w_p = [\int_0^L \mathrm{d}z/(L w_{xp}(z) w_{yp}(z))]^{-1/2} = 170\ \mu$m. With these parameters, the values obtained for the thermal and Kerr lens dioptric powers are $D_{\mathrm{Kerr}} = 424\ \mathrm{m^{-1}}$, $D_{\mathrm{th}} = -1.6\ \mathrm{m^{-1}}$. This clearly indicates the dominance of the positive Kerr lens on the negative thermal lens effect. Taking these parameters into account, we adjust the arm lengths of the cavity to maximize the stability discrimination of the Kerr lens between the cw and cwML regimes. A very stable cwML regime is obtained with 99 fs pulses. The corresponding spectrum is centered at 1053.4 nm (see Fig. 2) and has a bandwidth of 13.2 nm. The corresponding time-bandwidth product is 0.35. The repetition rate is 113 MHz, giving a laser output peak intensity of 38 kW and 2.9 MW intracavity. The shortest pulses do not correspond to a cavity optimized for the maximum power but to an enhanced soft-aperture KLM. In fact, 595 mW ML regime can be generated by adjusting the arm lengths of this cavity, but in this configuration, the shortest pulses have a pulse duration of 121 fs with a corresponding spectrum of 10.7 nm.

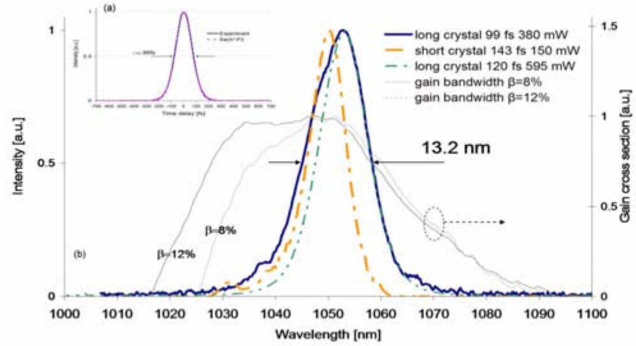

Fig. 2. (Color online) (a) Autocorrelation and (b) spectrum for the shortest pulses obtained in a stable cwML regime. (b) also shows the spectrum obtained with the short crystal and the normalized gain cross sections of Yb:CaF_2 for $\beta = 8\%$ and 12%.

One might think that the generation of shorter pulses compared with [8] is mainly due to a higher population inversion, leading to a spectral broadening of the gain. The population inversion is quantified in Fig. 2(b) by the ratio of the upper-level population to the total population β. If this hypothesis is valid, the use of a shorter crystal should allow further reduction of the pulsewidth. Another experiment has been carried out to test this interpretation with a 1.5-mm-long 3%-doped Yb:CaF_2 crystal on the same setup presented Fig. 1. In that case the shortest accessible pulse duration is 143 fs. The spectrum is centered at 1050 nm, and the bandwidth is 8.3 nm [Fig. 2(b)]. The blueshift is a signature of a higher β value. The average power is 150 mW for a 2% output coupler. In the short crystal experiment, the β value is increased, but the Kerr lens (KL) dioptric power is reduced by a factor 24 compared with the long crystal one, and no shorter pulses have been produced. These results indicate that the generation of shorter pulses in our experiment is due to KLM and Kerr-induced spectral broadening in the crystal rather than higher population inversion.

To experimentally investigate the contribution of the Kerr lens effect on the stabilization process of the cwML regime, we explored the stability range of this regime for the 6.1-mm-long crystal cavity. The dispersion of the cavity was tuned by moving the prisms in order to find other regimes in competition. We obtained a stable cwML over 400 fs^2 (by translating the prisms) with a pulse duration ranging from 170 fs down to 99 fs. In this range, long-term cwML was observed, and the negative thermal lens had no influence on the stability. Outside of this range, only Q-switch (QS) laser operation at a repetition rate around 13–14 kHz was obtained. The pulse duration was 3 μs with a pulse peak power of 9 W (730 W intracavity). Experimentally we did not observe other stable regimes such as multipulsing or Q-switch mode locking (QSML). However, a metastable regime was observed, in a small dispersion range located at the transition between short-pulse cwML and QS (Fig. 3). In this domain, we observed a slowly (~1 Hz) switching regime alternating between ML and QS. This characteristic time indicates a role of thermal effects in this process. This alternating regime could oscillate from ML to QS for hours without stabilization of one or the other regime. No other different regimes were observed except for a unique QSML pulse always occuring at the transition from cwML to QS (Fig. 4). This transition with the unique QSML pulse was very reproducible: It always started with soliton destabilization, around 67 μs later the QSML pulse appeared, and then 89 μs later the QS regime started with a constant period (77 μs). In this metastable regime the cwML pulses had a duration of ~97 fs. This regime may be explained as follows. In this parameter's range, at the frontier of the stability zone for mode locking, a small thermal perturbation might be enough to switch the operating regime. Starting in a ML regime, where the average laser power is higher (380 mW for ML and 350 mW for QS), pump absorption is higher (owing to pump absorption saturation), which leads to a hotter crystal. This temperature change is translated into negative thermal lens by the thermo-optic behavior of CaF2. This, in turn, stabilizes the cavity for the QS regime, because the KL is less discriminating. From this QS regime, the decreased power induced by SESAM losses leads to less pump absorption, a cooler crystal, and destabilization of the QS operation back to the ML regime, to complete a full bistable cycle. Owing to the KL, this bistable regime also oscillates between two different spatial modes (Fig. 4), a circular one for the ML and an elliptical one for the QS. In the ML regime, double pulsing or continuum shedding has not been observed, probably because these regimes are not stable: At the power level required for these regimes, the laser cavity allows only QS.

In conclusion, we have demonstrated for the first time (to our knowledge) the generation of sub-100 fs pulses with an Yb:CaF_2 crystal, the shortest pulses

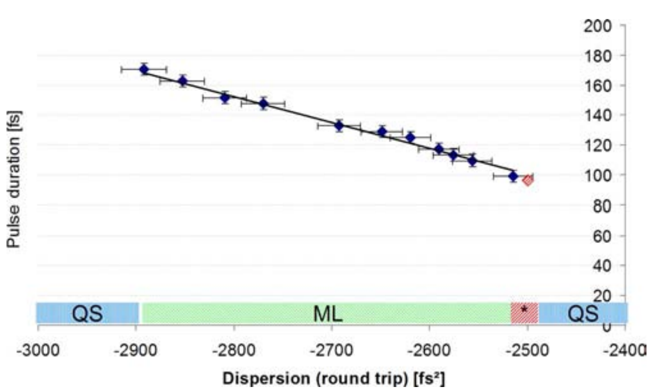

Fig. 3. (Color online) Observation of the different regimes: output pulse duration versus intracavity dispersion. Pulse duration is indicated for stable cwML and metastable QS/ cwML (*) regimes.

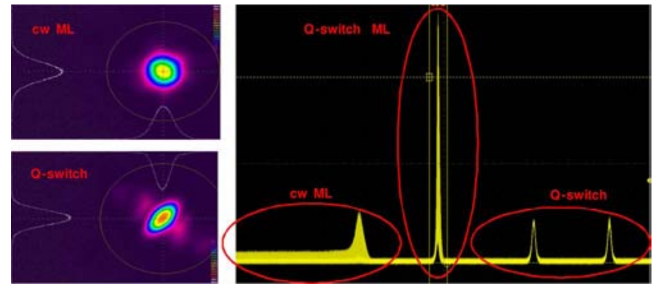

Fig. 4. (Color online) Transition between cwML and QS operation in the metastable regime.

ever obtained for this crystal. The corresponding average power is 380 mW, and the spectrum is centered at 1053 nm with a bandwidth of 13.2 nm. Despite its very broad emission spectrum, this crystal had never been used before to generate very short pulses owing to its long lifetime counteracting soliton stabilization. We have succeeded by using the Kerr lens effect to stabilize the cwML regime. Shorter pulses have been observed in an unstable regime where the uncommon negative thermal lens of fluoride seems to counteract the stabilization of cwML.

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